The HYDRODYNAMICS Group
studies in mass and energy transport in the earth

The HARTMAN Scenario Implications for WIPP

prepared for: **NEW MEXICO ATTORNEY GENERAL**

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EXECUTIVE SUMMARY

The Hartman # 2 Bates Well Blowout

Our review of the data continues to indicate that the blowout of the Hartman # 2 Bates well is best explained as a hydrofrac in the lower Salado Formation that extends from the Texaco Rhodes-Yates Waterflow to the well. This is the consensus of most investigators that examined the empirical data.

DOE and Sandia dismiss the interpretation that a hydrofrac happened at the # 2 Bates well.

LEFM versus BRAGFLO

Linear Elastic Fracture Mechanics (LEFM) is a widely used and accepted model for fractures including hydrofracs. BRAGFLO when compared to LEFM underestimates fracture radius by a factor of 5 times. Our review of the Sandia data does not present sufficient information to select the "porosity model" used in BRAGFLO over the "aperture model". Numerous internal documents indicates Sandia's concern about this problem. Use of a flow model such as BRAGFLO, whether it uses the porosity model or the aperture model, to estimate the extent of hydraulic fractures is at best an ad-hoc procedure. ***BRAGFLO in its current implementation is an inadequate model to predict the extent of hydraulic fractures.***

Stoelzel and Swift (1997) use BRAGFLO to compute hydrofrac radius. Their analysis is non-conservative in that they:

1. assume uniform permeability in the entire annular space between the borehole rock wall and the casing; and
2. allow fluids to hydrofrac all the marker beds simulataneously.

These assumptions minimize the hydrofrac radius; they do not represent what happened at the Hartman # 2 Bates well.

Scenarios

We conclude that three scenarios described in Bredehoeft (1997) still pose problems; these are:

1. ***hydrofrac extends from a leaking injection well into WIPP at low pressure;***

2. ***hydrofrac extends from a leaking injection well into WIPP when it is at lithostatic pressure;***

3. ***hydrofrac extends through WIPP and encounters a poorly plugged well that leaks upward.***

Scenario number 3 has the highest negative consequences. It predicts that the containment criteria are significantly violated in a few years.

Chapter 1 INTRODUCTION

In March, 1997 Bredehoeft submitted a report to the EPA WIPP Docket entitled:

The Hartman Scenario: Implications for WIPP.

In the March report three scenarios were identified that involved hydrofracs created by a leaking injection well that pose problems for WIPP; these scenarios are:

1. ***hydrofrac extends from a leaking injection well into WIPP at low pressure;***
2. ***hydrofrac extends from a leaking injection well into WIPP when it is at lithostatic pressure;***
3. ***hydrofrac extends through WIPP and encounters a poorly plugged well that leaks upward.***

Sandia in a memorandum by Swift et al. (June, 1997) reviewed the Bredehoeft March Report and found it not to be a sound analysis. They dismiss the Hartman Scenario that involves a hydrofrac as one interpretation, but not their interpretation. They choose not to address the Hartman case. They dismissed the remainder of the report by addressing the analysis and making a number of minor points that they argue invalidated the thrust of the report.

Bredehoeft rebutted the comments of Swift et al. in a memorandum to the EPA WIPP Docket dated July 28, 1997. In the rebuttal Bredehoeft argued that Swift et al. had avoided the salient issue—***are there injection well scenarios, stemming from what happened at the Hartman # 2 Bates well, that could pose problems for WIPP?***

DOE argued, based upon work by Sandia (Stoelzel and O'Brien, 1996; Stoelzel and Swift, 1997), that the consequences of a leaking brine injection well are insignificant and can be eliminated from consideration on that basis. (They do not argue that a leaking injection well is a low probability event—at least not as their primary basis to screen it out of consideration.) Their most recent analysis,

> Stoelzel and Swift (1997), *Supplementary Analysis of the Effect of Salt Water Disposal and Waterflooding on WIPP:* WPO # 44158,

does not address what happened at the Hartman # 2 Bates well. In this investigation Stoelzel and Swift (1997) allow brine to simultaneously enter all the anhydrite beds in both the Castile and Salado Formations. This is not what we believe happened at the # 2 Bates well; there brine was encountered in one anhydrite layer in the Salado Formation.

WIPP Quarterly Meeting—Santa Fe, August 31, 1997

The Hartman Scenario was discussed at length in this meeting. Officials from both DOE and Sandia stated emphatically that they did not believe that the cause of the brine blowout was a hydrofrac that extended from the Texaco Rhodes-Yates Waterflood to the Hartman # 2 Bates well. A hydrofrac is a widely accepted interpretation of what occurred; a number of experts expressed this opinion. A court found in favor of damages for Hartman on the basis of the hydrofrac.

DOE by denying that a hydrofrac explains the blowout at the Hartman well can ignore its implications for WIPP.

Scope of this Report

What happened at the Hartman # 2 Bates well happened almost ½ mile below the land surface; what exactly occurred is a matter of interpretation. The weight of evidence suggests that it was a hydrofrac that extended within the lower Salado Formation from the Texaco Rhodes-Yates Waterflood to the # 2 Bates well. We review the data from the blowout in Chapter 2.

We have done additional work since the March Report utilizing Linear Elastic Fracture Mechanics (LEFM) that supports our earlier analysis. We believe LEFM is a good representation of the hydraulic fracturing process. We present this work in Chapter 3.

We also present a comparison in Chapter 3 of the LEFM model with the results of hydraulic fractures predicted by BRAGFLO. BRAGFLO when compared to the LEFM model underestimates the fracture radius by a factor of 5 times. ***We conclude that BRAGFLO as implemented is inappropriate for accurately estimating the extent of hydraulic fractures associated with WIPP.***

We present analyses of the three scenarios of concern in Chapters 4, 5 and 6. We intend these analyses to satisfy some of the criticisms in the Swift et al. (1997) comment that Bredehoeft's methods in the March Report were not adequately explained.

We do not address the probability of the scenarios we pose for WIPP. Rather our analyses assumes that an injection well leaks in such a way that brine is injected into one of the anhydrite marker beds associated with WIPP—Marker Bed 139, for example. We ask—what might happen?

Chapter 2 The Hartman # 2 Bates Blowout

Introduction

Waterfloods are the most universal method of secondary recovery for oil; they are common practice throughout the world. Van Kirk (1994) did an analysis of the Texaco Rhodes-Yates Waterflood and its impact on the Hartman # 2 Bates well. He observed, after extensive analysis, that it is not uncommon for brine injected in waterflood operations to end up in strata other than the target zone. Texaco's wells in the Rhodes-Yates Waterflood experienced water flows in the Salado Formation.

Ramey's (1976) memo to the Secretary of the New Mexico Energy and Minerals Department records "*numerous*" severe water flows in Lea County, attributed to injected water escaping the target zone, penetrating the salt section, and moving laterally. An industry committee studied the problem in the Vacuum Field, and recommended shutting-in certain waterfloods for a period in an effort to identify leaking wells.

The Vacuum Field Geological Committee reported in 1987 on numerous instances of high-pressure, high-volume water flows encountered in the Salado Formation. A total of 48 flows of interest were examined. The Committee reported that fluid flow was facilitated both by dissolution and by mechanical fracturing—hydraulic fractures. The Committee concluded that large volumes of fluid can be stored in and along underclays and underclay-evaporite interfaces without the formation of large vertical solution cavities. Examples of Salado water flows include Texaco's Central Vacuum Unit # 169 (Van Kirk, 1994).

NMOCD records list 189 water flows encountered near waterflood operations in District 1 (Curry, Lea, Roosevelt, and part of Chavez Counties) in southeastern New Mexico during the period 1978 through 1992. The NMOCD files also indicated severe water flow problems in the Eunice-Monument area in the 1970s.

Bailey's (1990) memo reports, based upon the work of the Vacuum Field Salt Water Flow Geologic Committee, that there have been water flow drilling problems and numerous casing leaks in the Dewey Lake Red Beds, Rustler, and Salado Formations for many years. She goes on to state that large volumes of water travel laterally along bedding planes of the clastic-evaporite sequence; in many instances brine from the Salado water flows can be identified by chemical analysis as reinjected produced water. Bailey states: *"casing leaks through the salt section are the most logical pathways for introduction of fluids into the Salado Formation."*

The evidence indicates that leaks are not uncommon associated with waterflood and reinjection operations.

The Hartman # 2 Bates Blowout—Empirical Facts

During drilling, the hole encountered a substantial flow of brine at a depth of 2240 feet in the lower part of the Salado Formation. The flow of brine was uncontrollable; the highest flow rate was 1200 barrels per hour (840 gpm). The well flowed for four days; the quantity of brine hauled away is given in Table 2.1:

Table 2.1 Brine hauled from the Hartman # 2 Bates blowout (Van Kirk, 1994).

Date	Quantity Hauled (bbls)	Quantity Hauled (m^3)
16 January, '91	9,220	1466
17 January	14,130	2246
18 January	3,420	544
19 January	4,080	649
Miscellaneous	4,710	749
Total	35,560	5654

The shut-in pressure for the blowout zone was 1000 psig at the land surface. According to Van Kirk (1994): *"this is a reflection of a very high down-hole pressure which equates to a pressure gradient of 0.966 psi per foot of depth."* The weight of overburden, the vertical lithostatic stress, is equivalent to a pressure gradient of 1.0 psi per foot. In the blowout zone the fluid pressure is approximately lithostatic.

The Experts' Opinions

Van Kirk (1994) concluded *"there are three main reasons why the Rhodes Yates Waterflood was the source of the Bates # 2 water flows:"*

1. *"TIMING—Wells drilled prior to the waterflood operations had no recorded water flows in the Salado. A prime example is the Bates # 1 well, 100 feet west of the Bates # 2 well and drilled in 1953, with no reported water flows from the Salado. Water flows were first encountered by Texaco within the Rhodes Unit in 1979 and were within the Salado Formation.*
2. *HIGH-PRESSURES—The Rhodes-Yates Waterflood is the only waterflood in the area that had an injection gradient equivalent to or higher than the gradient observed in the Bates # 2 well.*
3. *INJECTION ABOVE FRAC GRADIENT—The available data indicates that some of the Rhodes-Yates Waterflood water injection wells have in the past and are continuing to inject water at pressures above the rock fracture pressure."*

Van Kirk in his trial deposition reported that a number of newer wells in the Texaco Rhodes-Yates Waterflood encountered water flows in the lower Salado Formation.

Powers examined the Hartman # 2 Bates well data. He generally concurred with Van Kirk's conclusions. He also commented on the pressure gradient and the possibility that the Bates # 2 well encountered a natural brine pocket (Silva, 1996). Powers states:

1. *"Typically, the measured pressure gradients from brine reservoirs in either the Castile or the very low flows in the Salado are considerably less than 1 psi per foot, ranging down to 0.8 psi per foot or less. The difference in pressure can be used to distinguish between natural or human induced occurrences."*

Powers went on to interpret what occurred at Hartman # 2 Bates well; he states (Silva, 1996):

2. *In the Hartman case, one has to either accept a natural cause or, if it is not natural, one must believe that fluid was transmitted along a bedding plane to the Bates lease perhaps for a distance of two miles.* ***Transport along the bedding plane is the best explanation.***

Transmissivity of the Blowout Zone

Bredehoeft (1997) in the March Report estimated the transmissivity of the blowout zone based upon specific capacity. A more accurate estimate of transmissivity can probably be obtained by using the record of flow as given in Table 2.1. (Transmissivity, T, is defined below.) Figure 2.1 is a plot of the average flow rate for the four days of data versus a calculated flow rate for a free flowing well (Lohman, 1972). The best fit value for transmissivity is 3×10^{-5} m^2/sec. This value is lower than the earlier estimate in the March Report, 1.4×10^{-4} m^2/sec, and is probably a better estimate for the equivalent transmissivity than that presented by Bredehoeft (1997).

We now believe the estimated transmissivity represents the equivalent transmissivity of a hydrofrac. Rather than divide the transmissivity by the thickness of the stratigraphic interval that produced the blowout in the # 2 Bates well to obtain a hydraulic conductivity, as Bredehoeft did in the March Report; we assume our new estimate represents an equivalent hydraulic conductivity (permeability) of the hydrofrac. In other words, we are assuming that the transmissivity and the hydraulic conductivity are equivalent in this instance, and describe the ability of the hydrofrac to transmit brine. The value for equivalent hydraulic conductivity is 3×10^{-5} m/sec.

A value of hydraulic conductivity of 3×10^{-5} m/sec (permeability—3×10^{-12} m^2) is approximately 5 orders of magnitude higher than the highest in-situ permeability measured at WIPP. We assign this value to the hydrofrac in the calculations that follow—Chapters 4, 5, and 6.

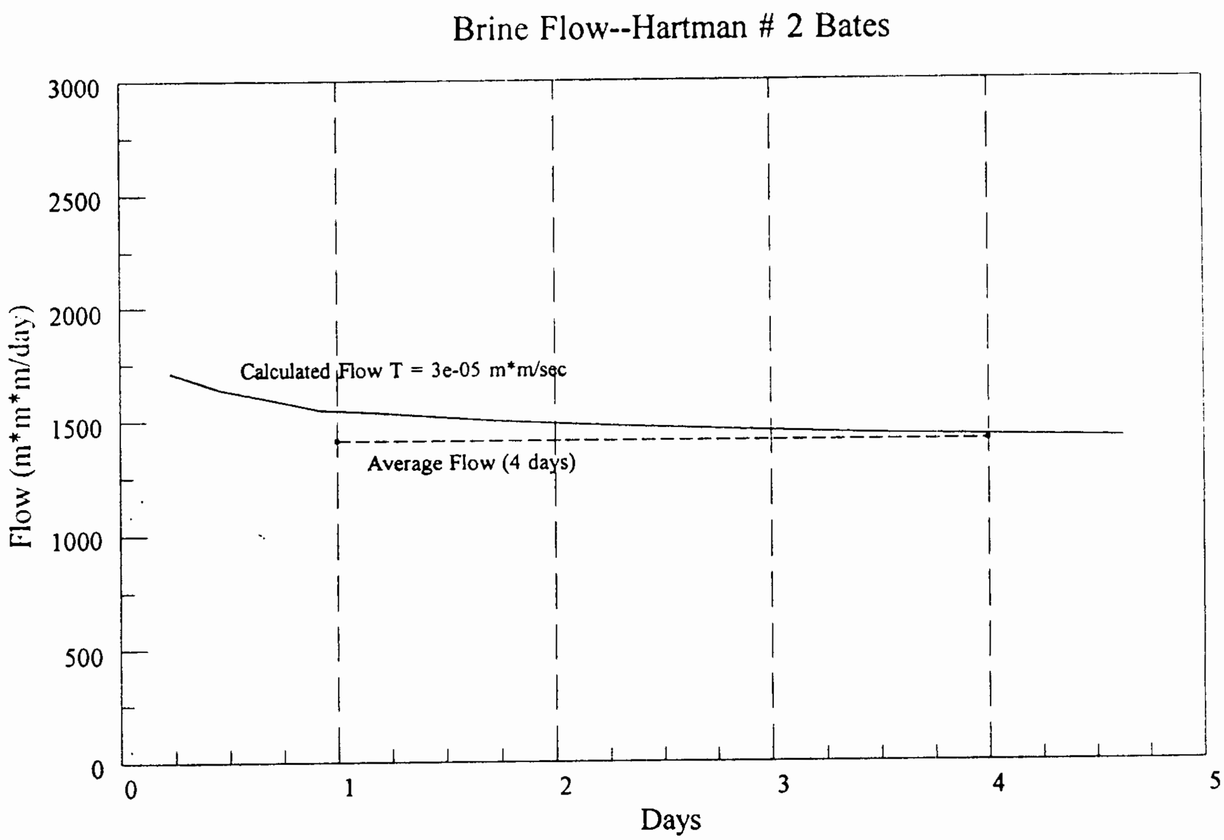

Figure 2.1 Average flow from the Hartman # 2 Bates blowout zone fit to a theoretical calculation for a flowing well (Lohman, 1972).

Flow from the Yates Formation

One alternative explanation, suggested by DOE and Sandia officials, is that the blowout involved a flow path up the # 1Bates well from the Yates Formation through the Salado anhydrite to the # 2 Bates well.

We made an attempt to analyze this scenario. In order to do the analysis we need a transmissivity for the Yates Formation. We obtained core permeability data for 3 boreholes in Lea County from the New Mexico Bureau of Mines and Mineral Resources, Office of the State Geologist in Socorro; the three wells are:

1. Gulf # 1-I Janda — section 2-23S-36E, drilled in 1949;
2. Cities Service # 13-B Closson — section 30-22S-36E, drilled in 1957;
3. Continental # 1 Farney-Federal "A-17" — section 17-23S-36E, drilled in 1957.

There were 100 or more laboratory core permeability determinations in the Yates Formation in each well. Figure 2.2 is a plot of the core data. The data is referenced to the base of the Yates Formation. It is interesting how the same zones of permeability show up at the same elevations above the bottom of the formation; this is seen best on the linear plot of permeability versus elevation above the bottom (Figure 2.2).

The Gulf # 1-I Janda well has the highest Yates transmissivity. The transmissivity can be defined as (Lohman, 1972):

$$T = \sum_{n=1,2,3} b_n K_n$$

where b_n is the thickness of a bed for which the hydraulic conductivity (permeability), K_n , is measured. For the Gulf # 1-I Janda well the transmissivity of the Yates Formation is 1967 millidarcy-ft (an oil field unit) which translates to 6×10^{-6} m^2/sec. This compares to 3×10^{-5} m^2/sec indicated for the blowout zone above. The transmissivity of the Yates is lower than the blowout zone, but these estimates indicate there is less than an order of magnitude difference.

In Figure 2.3 we compare the calculated flow from the Yates Formation with a transmissivity of the Gulf # 1-I Janda hole with the Hartman # 2 Bates well blowout zone. The calculated flow from the Yates Formation is significatly lower than that observed for the blowout.

This analysis is only suggestive. We do not have core analysis for the Yates in the vicinity of the Bates lease. Permeability is known to vary widely in all natural materials. Our analysis suggests that the brine encountered in the Hartman # 2 bates well did not come directly from the Yates Formation.

Conclusions

Dennis Powers (Silva, 1996) stated it best: "***Transport along the bedding plane (in the Salado Formation) is the best explanation.***" The weight of the evidence suggests fluid flow in the Salado Formation from the Texaco Rhodes-Yates Waterflood to the Hartman # 2 Bates well. We will show below that this probably involved a hydraulic fracture.

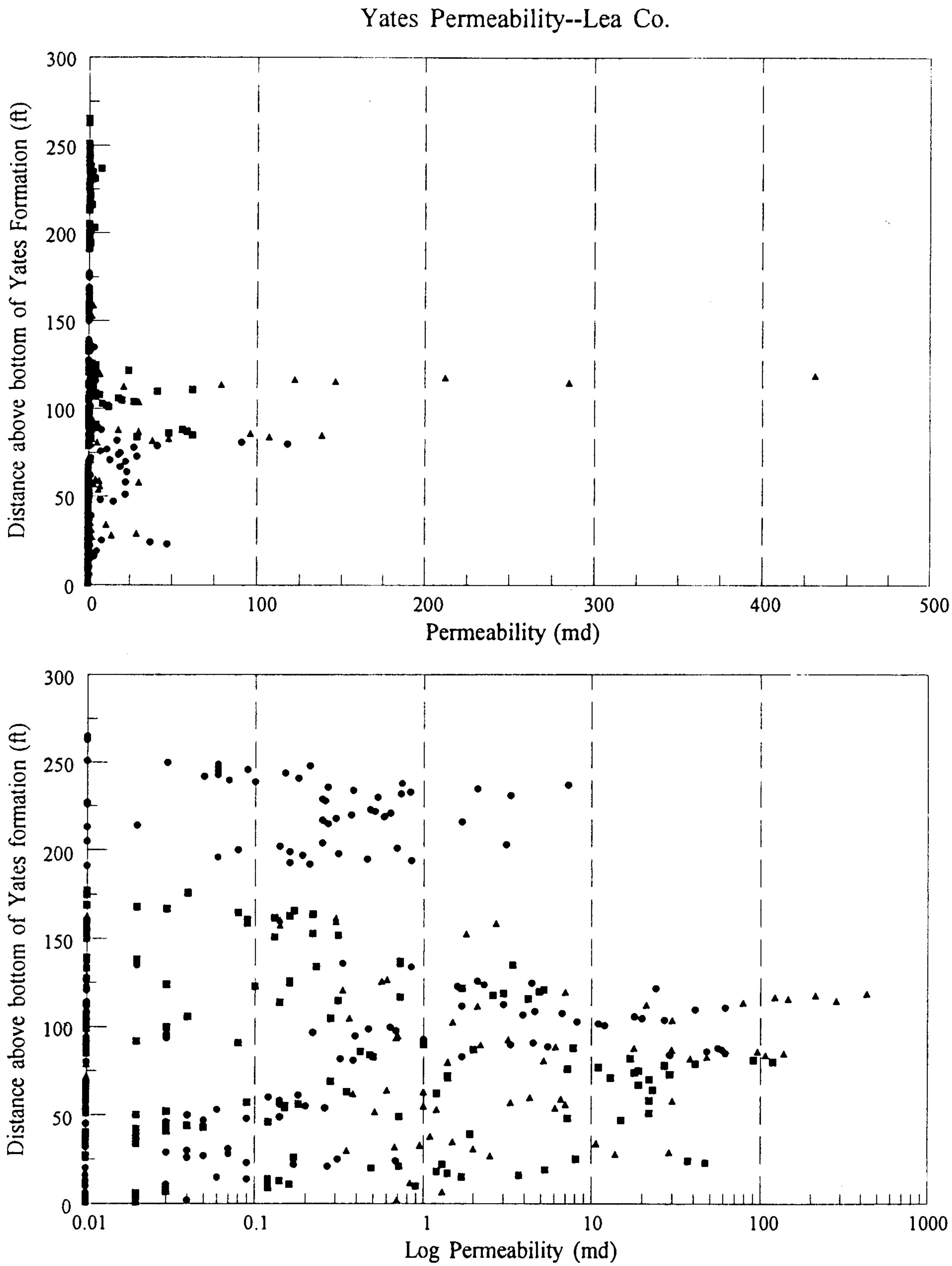

Figure 2.2 Plots of permeability versus elevation above the bottom of the Yates Formation for three wells in Lea County. The highest permeabilities are for the Gulf # 1-I Janda well (diamonds on the plots).

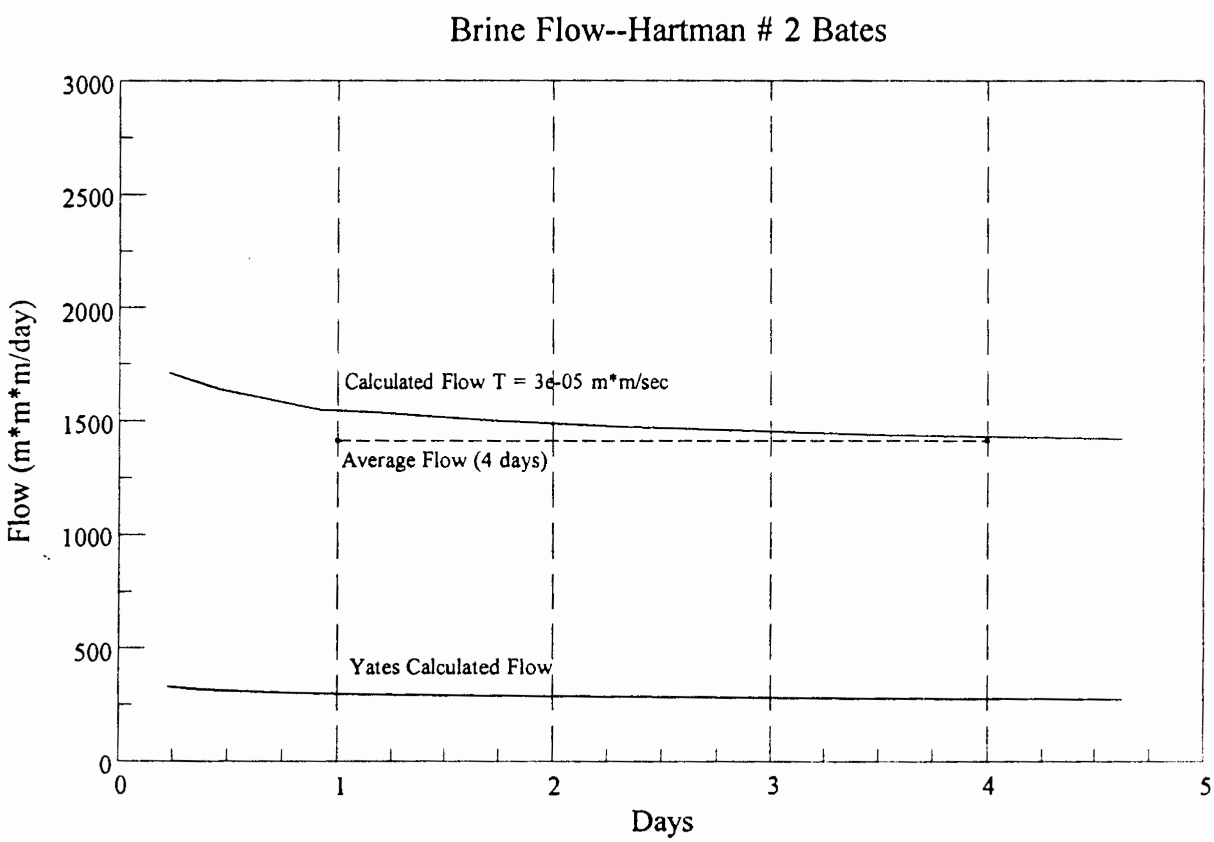

Figure 2.3 Plot of calculated flow from the blowout zone and a Yates well with the transmissivity of the Gulf # 1-I Janda well.

Chapter 3 LEFM—Hydraulic Fractures

Introduction

Linear Elastic Fracture Mechanics (LEFM) is a classical field of mechanics that has evolved during the twentieth century. It is by far the most well developed and clearly understood model for fractures. There are many textbooks on fracture mechanics. For an introduction to LEFM we refer one to Broek (1974) or Anderson (1989). A good summary of models for hydraulic fractures is found in Rubin (1993), which also contains an extensive list of references on the subject. Other examples of the literature on modeling of hydraulic fractures are given in Shlyapobersky and Chudnovsky (1994), Pollard and Holzhausen (1979), and Petitjean and Couet (1994).

Because of its relative simplicity, LEFM is the prevailing model for describing hydrofracs. Although LEFM does not provide good predictions of hydrofrac behavior in all situations, it provides reasonable predictions in many geological settings. It has been shown that LEFM is an excellent model for large hydrofracs in the WIPP setting (Arguello and Stone, 1994: Gerstle, et al., 1996).

Hydraulic Fractures from LEFM

We envision a simple system. A hydrofrac is created by injection into one of the Salado marker beds—Marker Bed 139, for example. In plan the hydraulic fracture is circular. It grows radially outward as fluid continues to be injected. As the fracture grows it encounters a second borehole, and flow can occur up the second borehole.

We use a finite element model to model the hydrofrac. A number of parameters, including the elastic properties of the rock, need to be specified. The model generates a number of outputs. Table 3.1 is a list of input and output parameters (Gerstle et al., 1996):

Table 3.1 Inputs and Outputs from the LEFM fracture model.

INPUTS	**Model Value**		
Poisson's Ratio for the salt	0.25		
Young's Modulus	31,000	MPa	
Fracture Toughness	0.5	MPa $m^{1/2}$	
Depth to the Fracture	659	m	
assumed weight of overburden	2100	Pa/m	(1.0 psi/ft)
2^{nd} borehole when present			
distance	3000	m	
hydraulic conductivity	variable	m/yr	
OUTPUT			
Crack Length		m	
Crack Opening Displacement—centerline		m	
Crack Volume		m^3	
Pressure in Excess of Lithostatic		MPa	

The LEFM model treats the injected water as if it is incompressible. All the water is assumed to be stored in the fracture until there is some mechanism for outflow—another well, WIPP, etc. Without outflow the extent of the fracture is purely a function of the volume of water injected.

Figure 3.1 is a cross-section along the radius of one of the fractures produced by the LEFM model. Figure 3.2 is a plot of growth of a hydrofrac over time for a hypothetical fracture with an injection rate of 50,000 m^3/yr; it shows the fracture extending to 3 km in approximately 400 days at this injection rate. Figure 3.3 shows the vertical displacement at the center of this fracture.

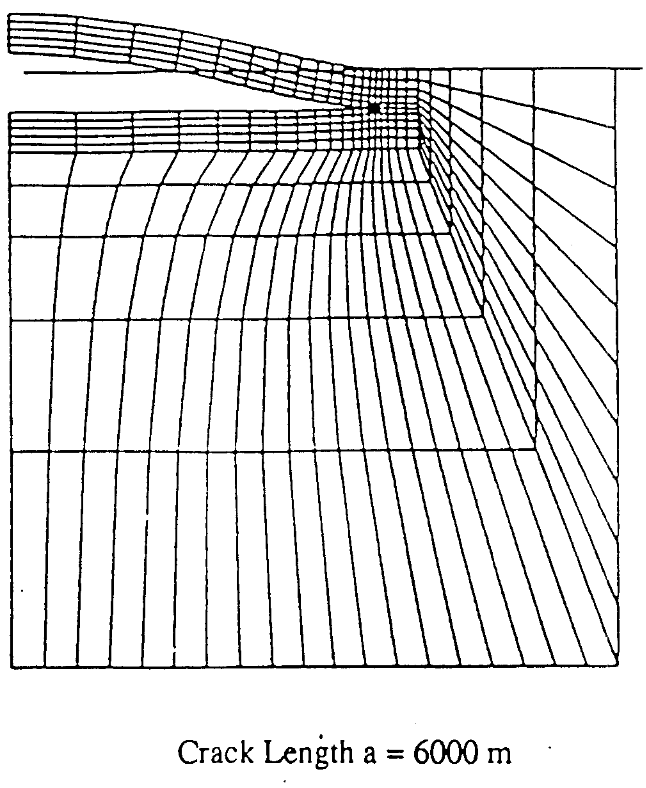

Figure 3.1 Cross-section of a fracture along the radius showing the finite element mesh.

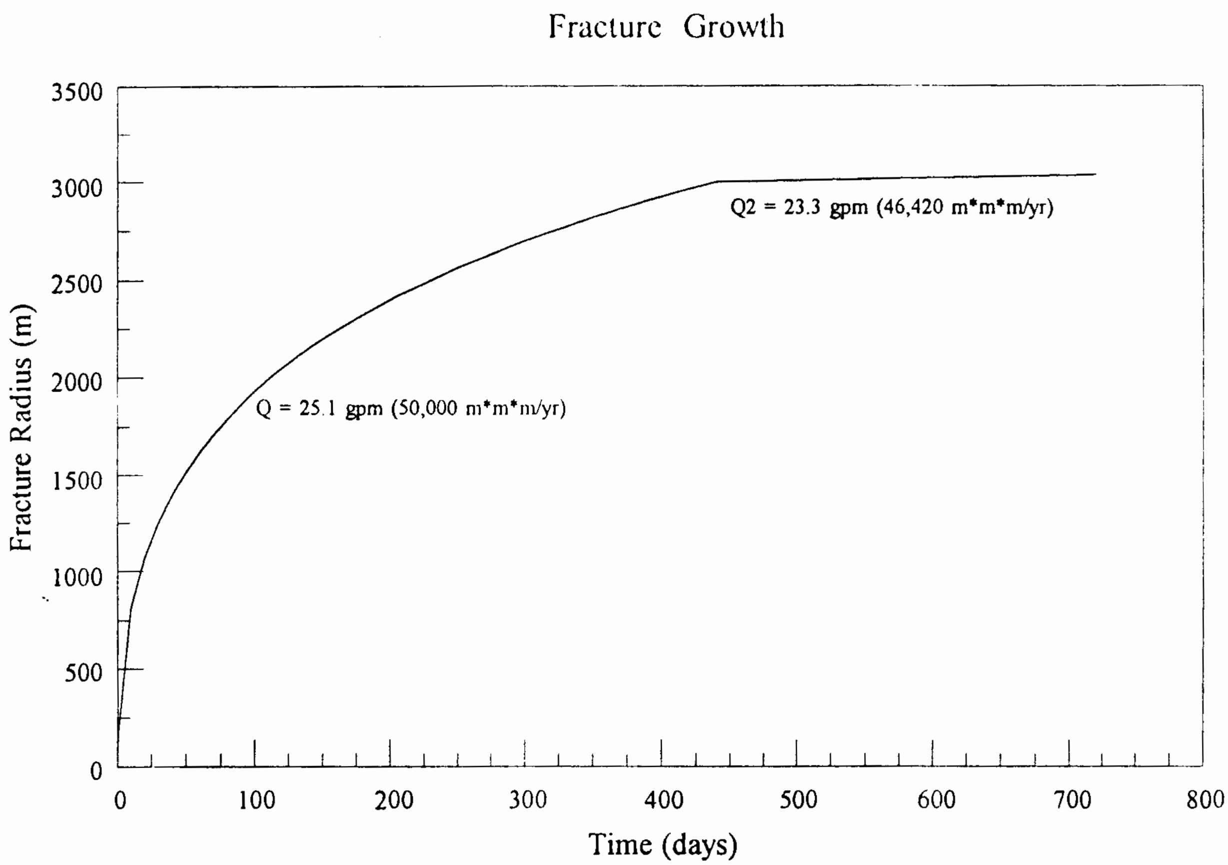

Figure 3.2 Plot of fracture radius versus time for a fracture with an injection rate of 50,000 m^3/year. At a radius of 3000 m the fracture encounters a leaking outflow well.

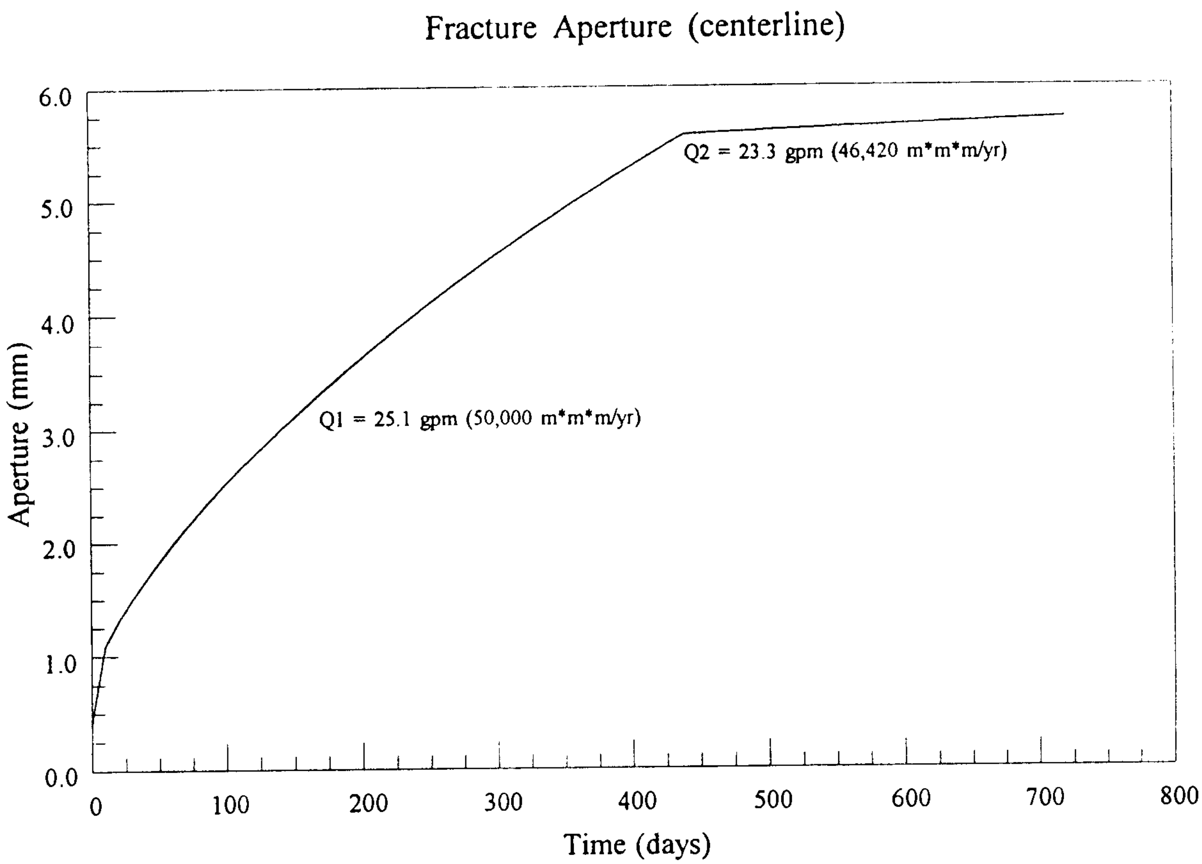

Figure 3.3 Plot of vertical displacement at the centerline versus time for the fracture illustrated in Figure 3.2. At approximately 400 days the fracture encounters an outflow well.

Quantities of Injected Brine

Since the fracture extent is controlled entirely by the quantity of fluid injected, it is of interest to examine the reported volumes, simply to bound potential quantities. Table 3.2 is a list of reported volumes:

Table 3.2 Reported volumes of brine injected in the area of WIPP.

Reporter	Volume bbls/day	Volume m^3/yr
Ramey (1976)—typical waterflood	5000-6000	350,000
Bailey (1990)—typical injection well	1000-2000	115,000
LaVenue (1991)	414	23,700
LaVenue(1991)	960	55,800
David Ross AIT # 1 Federal (Silva, 1996)	3333	193,000
Todd 36 Federal # 3 (Silva, 1996)	1000	58,000
Pogo Oil (Silva, 1996)	1000	58,000
Cabin Lake Unit (Silva, 1996)	3069	178,000
Typical New Mexico (Kreitler et al., 1994)	3850	223,000
San Juan Basin (Krietler, et al., 1994)	4399	255,000
San Juan Basin (Krietler, et al., 1994)	6854	398,000

There was discussion during the Hartman trial of how much fluid was unaccounted for in the Texaco Rhodes-Yates Waterflood. The consultants for Hartman estimated that 20,000,000 barrels of brine (3,000,000 m^3) were unaccounted for; Texaco argued it was not that much.

A Hartman # 2 Bates Hydraulic Fracture

The most likely shape for a hydraulic fracture is circular; however the injection well is not necessarily located at the center of the circular fracture (Wawersik and Gerstle, 1996). In experimental fractures made in the laboratory the injection well is often located away from the center of the fracture, nearer the edge.

Figure 3.4 and 3.5 show the radius of fractures predicted by the LEFM model versus the quantity of brine injected. These figures were prepared for Marker Bed 139 at WIPP. The zone that blew out at the # 2 Bates well is slightly deeper, by approximately 20 m. For our purposes Figure 3.4 applies equally well to the blowout zone.

The Hartman # 2 Bates well is 2 miles from the Texaco Rhodes-Yates Waterflood. If the radius of the fracture is centered at the Rhodes-Yates Waterflood the fracture radius needs to extend approximately 3.33 km to reach the # 2 Bates well. If the input well was off center near the edge of the fracture, as laboratory experiments sometimes suggest, the radius could be reduced to slightly more than ½ the distance between wells, perhaps as low as 1.7 km. This indicates that the volume of fluid that needed to be injected to create the fracture ranged from 15,000 to 95,000 m^3 (94,000-600,000 bbls). As suggested above there may be 20,000,000 bbls (3,000,000 m^3) of brine unaccounted for at the Texaco Rhodes-Yates Waterflood. The amount needed to create the hydrofrac is a small fraction of the amount lost.

If the loss of fluid at the Texaco Rhodes-Yates Waterflood is as high as Hartman's consultants argued, 3,000,000 m^3, then the LEFM calculations suggest a hydraulic fracture with a radius of 8 km could be generated.

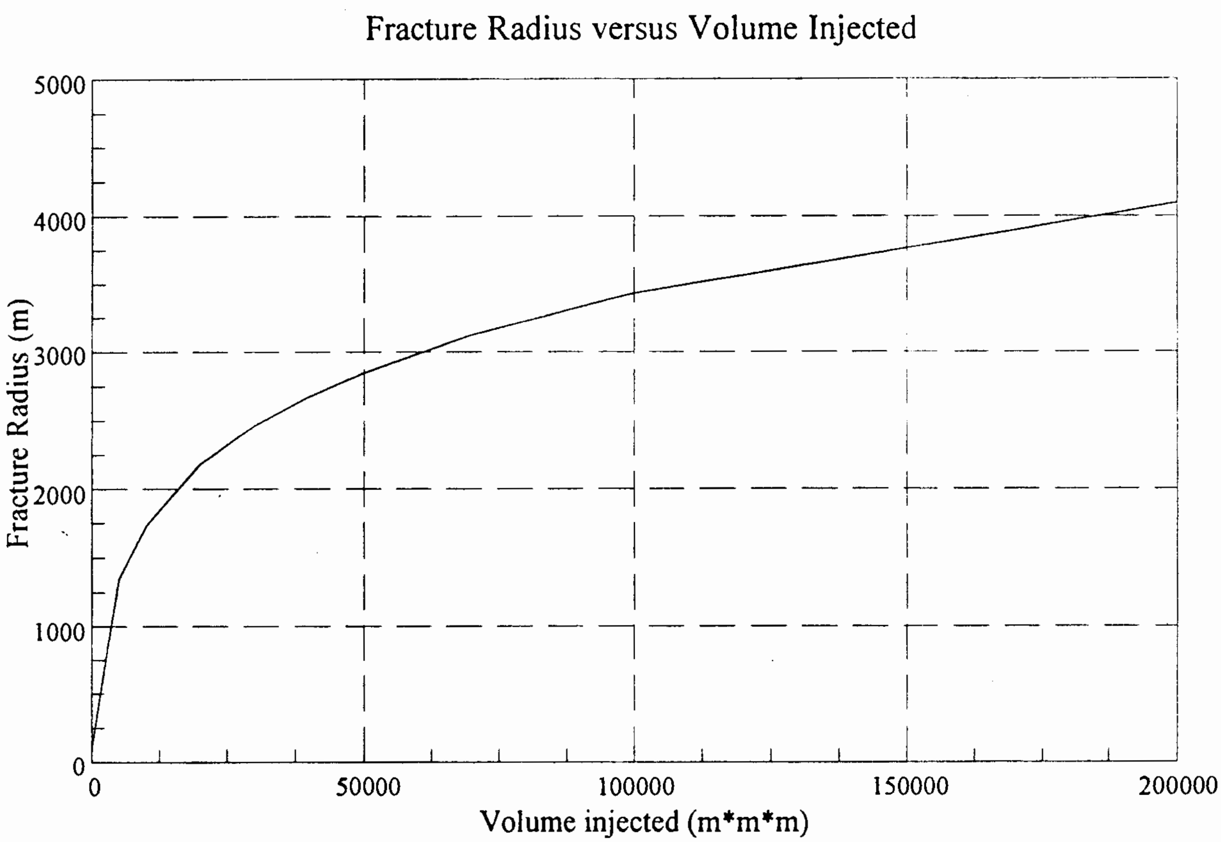

Figure 3.4 Plot of hydraulic fracture radius versus volume of fluid injected.

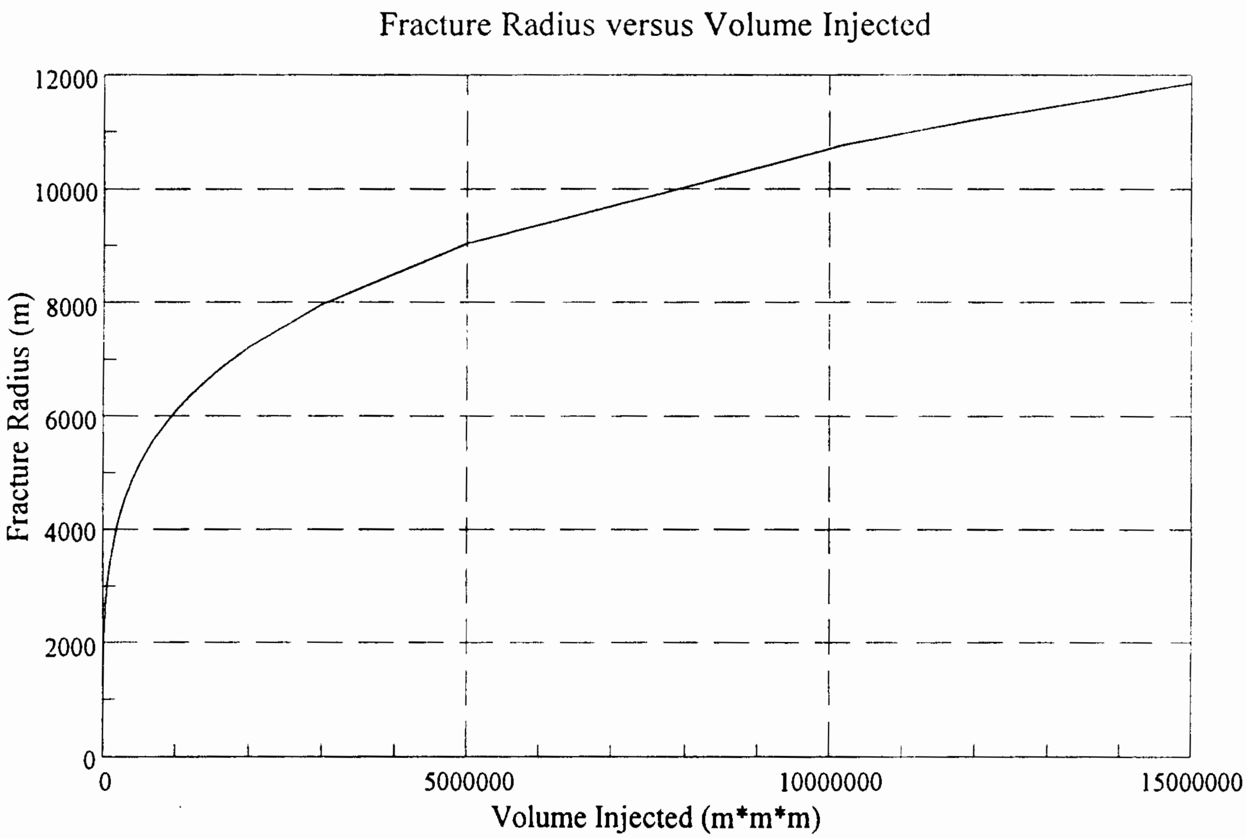

Figure 3.5 Plot of hydraulic fracture radius versus volume of fluid injected—larger volumes.

Bredehoeft's Flow-Hydraulic Fracture Model

In the March Report, Bredehoeft (1997) used his flow model to approximate hydraulic fractures. The algorithm for approximating the effects of hydraulic fracturing was to increase the permeability (hydraulic conductivity) to that estimated for the Hartman # 2 Bates blowout zone (3×10^{-5} m/sec) when the pressure in any cell in the model domain exceeded lithostatic. The permeability change was introduced as a step function. Bredehoeft did not change the porosity as the fracture was created; he argued that the aperture of the fracture is small and makes a negligible change in porosity. The fact that the porosity was not increased was the subject of criticism in the Swift et al. (1997) comment.

Using a flow model to estimate the extent of hydraulic fractures is an ad-hoc procedure. A flow model is not designed to model fractures; it is designed to model fluid pressures. The complexity of the fracture process can only be incompletely approximated by this procedure. The approximation is subject to discretization errors associated with both the spatial mesh and the time steps size. Of critical importance is how the storage of fluid in the fracture with an aperture with a few millimeters is approximated by the flow model

A somewhat similar ad-hoc procedure to that used by Bredehoeft (1997) is used by Sandia in BRAGFLO; however, in BRAGFLO both a change in both porosity and permeability is introduced. The change in BRAGFLO is introduced gradually; a gradual change makes the numerical model more stable. Bredehoeft's model of hydraulic fracturing requires small time steps to insure numerical stability. We compared the Bredehoeft Flow-Hydraulic Fracture model to the LEFM model. Figure 3.6 shows the results of our comparison; the results compare favorably. The results are seen to be somewhat sensitive to the storage coefficient in the Bredehoeft model. Bredehoeft (1997) favored a storage coefficient of 1×10^{-5}; Figure 3.6 indicates that this value works well. Contrary to the Swift et al. comment, the fact that the porosity is not increased in the Bredehoeft model does not impact the results significantly. Still it should be remembered that this is at best an ad-hoc method for representing hydrofracs.

This comparison suggests that Bredehoeft (1997) was probably justified in using his model to simulate hydraulic fracture in the scenarios he analyzed associated with WIPP. A better model of the hydrofrac process would couple the flow model with LEFM. We conceptualized such a model; however we did not feel it was necessary for this report. In this report we use 1) LEFM to model the hydraulic fracture, and 2) then calculate flow through this fracture using a flow model.

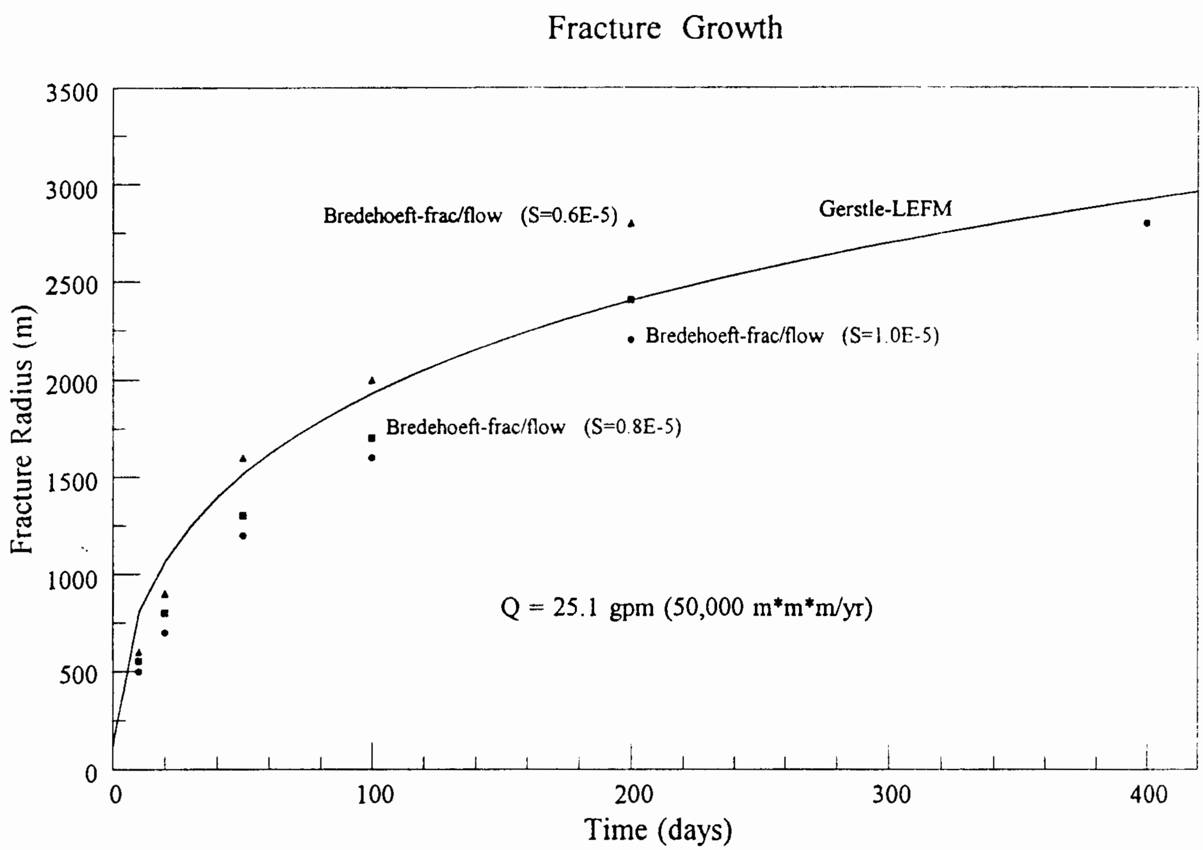

Figure 3.6 Comparison of the Bredehoeft Flow-Hydraulic Fracture model with the LEFM model.

BRAGFLO versus LEFM

In a LEFM model of a hydofrac, the extent of the fracture is purely a function of the quantity of brine injected, as shown above—see Figures 3.4 and 3.5. It is relatively easy to compare the extent of a fracture computed by BRAGFLO with that computed by the LEFM model. In the "radial models" analysis, results were presented for the extent of fracturing for both Marker Beds 138 and 139 (Stoelzel and Swift, 1997, Figure 16, p 45). Also included is the cumulative quantity of fluid injected (Stoelzel and Swift, 1997, Figure 8 and 9, p. 38). The results are compared to the LEFM model in Table 3.3:

Table 3.3 Comparison of BRAGFLO fractures versus LEFM fractures.

	Volume Injected (m^3)	**BRAGFLOW frac radius (m)**	**LEFM frac radius (m)**
Radial Model R8—MB 138	**1200**	**151**	**765** (calculated)
Radial Model R8—MB 139	**1400**	**151**	**800**+/- (Fig. 3.2)

BRAGFLO when compared to the LEFM model underestimates the extent of the frac by a factor of 5.

The appropriate fracture model has been a long standing issue within Sandia. PA uses the so-called *Porosity-Model* relationship, which is unsupported by experimental data. As shown above the Porosity Model underestimates the radius of the hydrofrac when compared to the established LEFM model. Through the years Sandia has numerous references to an *Aperture Model* that also fits the empirical data and gives quite different results. Larson and Davies (1993) in a memo to Martin Tierney point out there are two models to describe the permeability changes associated with hydraulic fractures; 1) the Porosity Model (now used by PA) and 2) the Aperture Model. The Larson-Davies memo appears to be the first place where the relationship between porosity and permeability is discussed;. I quote their memo (Larson and Davies, 1993):

*"The difference between the Aperture Model and the Porosity Model is the degree of permeability change associated with the interbed dilation. A graphical comparison of permeability versus porosity was prepared to illustrate this difference in behavior under different assumptions about critical input parameters (Figure 2—*Larson and Davies memo*). As shown in Figure 2, the Aperture Model has a rapid increase in permeability once the fracture dilation begins regardless of the number of active fractures, whereas the Porosity Model has a gradual and nearly linear increase in permeability. The Porosity Model requires values of J of about 40 to attain permeabilities similar to the Aperture Model at a porosity of 0.02 if the initial porosity (matrix porosity) is 0.01. However, it is apparent from the graph that the two conceptual models are incompatible, i.e. no selection of parameters can make the shape of the porosity-permeability correlation in the Aperture Model look like that in the Porosity Model. Because of this difference, it is important to assess whether the effects of the difference warrant adopting a new correlation for use in Performance Assessment calculations.*

Beauheim et. al. (1994) again point out that there are two alternative models to describe the permeability of fractured anhydrite: 1) the Porosity Model; 2) the Aperture Model. They argue both models can be made to fit the empirical data. ***They suggested additional experiments to distinguish between the competing models. The definitive experiments involved measuring the strain during hydraulic fracture experiments. These experiments were not conducted. As a consequence, the porosity model used by PA is unconfirmed by experimental results.***

Freeze et al. (1995) discuss the alternative aperture model; they go on to state:

Because of the higher predicted permeabilities the aperture model will propagate fracture-altered properties away from the repository, and will likely increase gas migration distance (Freeze et al., 1995).

Larson (1997) in a memo to Lori Dotson gives Beauheim et al.(1994) Figure 14 as a reference for changes in the porosity-permeability model. Figure 14 (Beauheim et al., 1994) shows data less than an order of magnitude change in permeability with an 8 MPa change in confining pressure. This is a small change associated with a large change in pressure. The experimental data were for loading in compression which is not the same as increasing the pore fluid pressure.

As we examine the references that describe the experimental anhydrite hydrofrac data, neither Beauheim et al. (1993) nor Wawersik et al. (1997) address the issue of which of the proposed models—Porosity, or Aperture—better fit the empirical data. A problem with the hydrofrac experiments that were done is that they were conducted close to the repository where the influence of the mined opening impacted the results. Wawersik et al. (1997) estimated the fracture opening as approximately 3 mm. This small fracture was sufficient to explain the several orders of magnitude difference in permeability between the hydrofrac and the intact rock. Wawersik et al. (1997) refer to the applicability of LEFM to estimate both pressure and fracture distances in the experiments. In order to interpret the experiments one has to assume a geometry for the fracture. The fractures near the tunnels are probably different than they would be in the far field.

The Aperture Model, as described by Larson and Davies (1993), predicts a change in permeability ranging from 5 to 10 orders of magnitude with a small change in porosity. The major change in permeability occurs when the hydraulic fracture is created. Beauheim et al. (1993) in plotting the pressure during hydrofrac experiment shows that 1) the pressure increases rapidly in the interval to be fractured once pumping is initiated, 2) the pressure reaches a point where the hydrofrac occurs, and 3) once the fracture occurs the pressure drops down and stabilizes with continued pumping—the pressure is such to accommodate continued injection, maintain the fracture open, and extend it. This is a typical pressure plot for hydraulic fractures. The Aperture Model more nearly reflects the empirical data.

The best explanation for why the Porosity Model was chosen by PA seems to be expressed by Larson and Fewell in a memo to Chu (dated March 12, 1997). The explanation is twofold. We quote the following questions and answers from their memo:

Q. Why are there maximum porosity and permeability changes?
A. These are set to prevent the possibility of unphysical destabilizing values being calculated for fluid flow parameters in BRAGFLO……

Q. Why isn't a discrete-fracture model implemented in BRAGFLO?
R. The problem posed by dynamic fracturing of interbeds due to high gas pressure is not amenable to solution by models in existence……

Other work using linear fracture mechanics (Mendenhall and Gerstle, 1993; Gerstle, Mendenhall and Wawersik, 1996) indicates that some model <u>like</u> the Aperture Model is a more appropriate relationship to describe hydraulic fracturing associated with WIPP. As mentioned above, using a flow model to approximate the hydrofrac process is at best an ad-hoc procedure.

A Peer Review group reviewed the porosity fracture model used in PA and gave it their approval, presumably based upon a review of the data. However, two facts were missing from the review:

1. The experiments in which deformation was measured during fracturing were proposed but never conducted. There is no data on changes in porosity during hydrofracing.
2. There was not comparison between the BRAGFLO predictions of fracture radius versus another model—LEFM, for example. As we show above, BRAGFLO greatly underestimates the radius of fracing.

The Sandia empirical field data does not distinguish between the Porosity Model and the Aperture Model. The critical experiments to distinguish between the models were not done. PA has chosen to use the Porosity Model. When compared to a LEFM model, the Porosity Model implemented in BRAGFLO produces much shorter hydraulic fractures—by a factor of 5, as indicated above. BRAGFLO as implemented is inappropriate for accurately estimating the extent of hydraulic fractures associated with WIP. Using a flow model to approximate the hydrofrac process is at best an ad-hoc procedure subject to numerous errors.

Stoelzel and Swift (1997)

Stoelzel and Swift (1997) using BRAGFLO calculated the radius of hydraulic fractures associated with a leaking well. ***Their assumptions are non-conservative.*** They assume the borehole leaks near the bottom. The leaking fluid then goes into the annular space between the casing and the rock wall of the hole. They assume a uniform permeability for this space, and allow fluid to permeate all of the marker beds simultaneously. ***By assuming uniform borehole permeability and contact with all the marker beds they minimize the radial extent of fracturing.*** Boreholes in failure typically have higher permeabilities at the point of failure than elsewhere. Failure tends to focus the leaking fluid.

A more conservative approach is to assume that the fluid contacts one marker bed only. This will produce the maximum radius of fracture, the most dangerous case for WIPP.

As suggested above, we question that BRAFLO adequately represents the hydrofrac process.

Chapter 4 Flow to WIPP at Low Pressure

Introduction

In the Bredehoeft March Report (Bredehoeft, 1997) one scenario identified for concern was a hydrofrac that extended from an injection well just outside the WIPP land withdrawal boundary into WIPP. In this scenario WIPP was at low pressure. Figure 4.1 is a schematic diagram of the hydraulic fracture. The question was posed—what might happen?

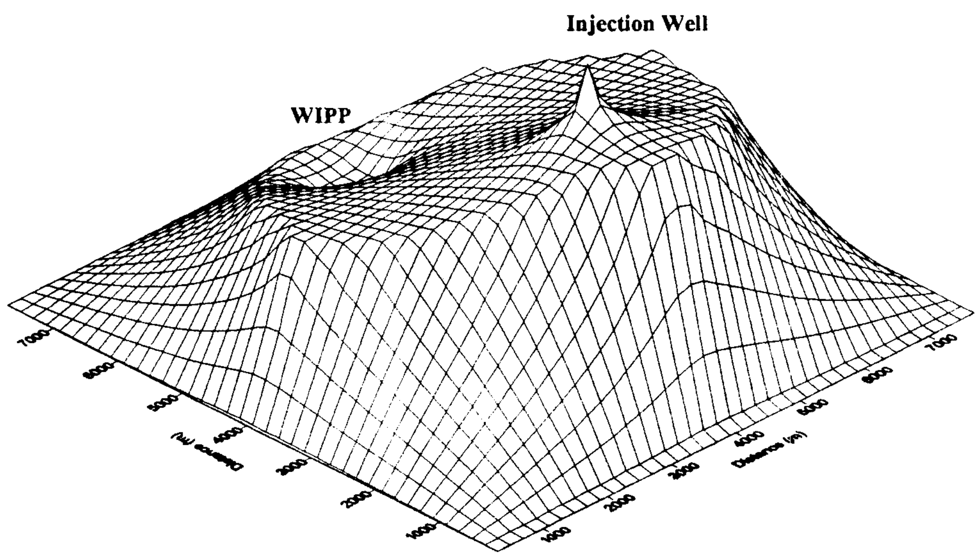

Figure 4.1 Schematic diagram of a hydrofrac extending to WIPP.

The Pulsing Scenario

Bredehoeft (1997) postulated a pulsing flow to WIPP. The mechanism suggested was: 1) a hydrofrac would extend into WIPP, 2) flow would occur from the fracture into the repository, 3) the flow would lower the pressure in the fracture and it would close, and 4) the process would repeat. The process would continue to repeat as long as injection continued.

Bredehoeft modeled this process. The model generated pulses of flow just as was hypothesized. The period between pulses varied as one might expect with such a highly non-linear model. The model demonstrated elements of chaotic behavior. Whether the model created chaotic behavior in the classic sense of chaos theory was unclear.

Pulsing flow appears to be a possibility; we see no reason to change the earlier analysis (Bredehoeft, 1997). Nevertheless, pulsing flow it is not the only possibility.

Initial Break Through into WIPP

A hydrofrac to encounter WIPP from outside the land withdrawal boundary needs to extend approximately 3.33 km (2 mi) from the well to WIPP. The size of the fracture depends upon whether the injection well is at the center of the fracture or out near the edge. Experiments suggest that an injection well location at the center or out toward one edge of the fracture is equally likely. In either case the fracture will contain a large quantity of brine.

In the case where the injection well is at the center of a circular fracture, the radius of the fracture will be approximately 3.33 km. If the injection well is near the edge of the fracture the radius of the fracture might be as small as 1.7 km. LEFM indicates that the brine volume in these fractures will range from a low 15,000 to a high of 95,000 m^3. WIPP mined openings are expected to consolidate quickly after filling; the pore volume within the filled and closed repository is approximately 50,000 m^3.

Most of the brine in the crack will flow into WIPP once the hydrofrac breaks through. The aperture of the fracture is such that the equivalent permeability of the fracture is high; there is almost no head loss due to flow in the fracture. While the physics of what happens on breakthrough into WIPP are not totally clear, one can anticipate a major amount of the brine in the crack to flow out and into WIPP. Depending upon the geometry of the fracture, the volumes are such that approximately one pore volume of brine can be quickly delivered as the hydrofrac encounters WIPP.

Continued Flow after Initial Breakthrough

The question arises as to what happens after the initial breakthrough. As suggested above, the initial breakthrough will place a substantial quantity of brine into WIPP; it may well fill the repository. There may be sufficient MgO to tie up some of the water chemically by forming the mineral Brucite. Our analysis (Bredehoeft and Hall, 1996) indicated the MgO probably could remove approximately one pore volume of brine ($\approx$ 50,000 m^3). However, once the capacity of the MgO is overwhelmed by more than one pore volume of brine, then a large quantity of free water will be in the repository. As the repository fills the pressure will rise both from internal gas generation and from the pressure of the injected water. As injection continues the pressure in the repository will tend toward the pressure of the injected fluid.

The anhydrite hydrofrac experiments in WIPP suggested that a hydrofrac, once it is generated, does not fully close (Beauheim et al., 1994; Wawersik et al., 1997). Approximately one third of the injected fluid remained in the fracture after their experiment. This indicates that a higher permeability pathway is created by the hydrofrac. The experiments also indicated that with pressure differentials of 1 MPa flow rates following hydrofracing were over two orders of magnitude higher than the prefrac rates.

Even if the pressure drops in a hydrofrac that extends into WIPP, flow will continue in the higher permeability pathway created by the fracture. As long as injection into the Marker Bed continues we can expect flow to WIPP. As WIPP fills and pressure becomes lithostatic the hydrofrac will tend to continue to extend outward. The hydrofrac will extend beyond WIPP; this leads to the two-well scenario described in Chapter 6.

Conclusions

A hydrofrac extending to WIPP from a nearby injection well will:

1. ***Place a large volume of brine into the repository simply from the amount of brine stored in the fracture (15,000 to 95,000 m^3). This water may be of sufficient volume to totally flood the repository.***

2. ***Continued injection into the Marker Bed will continue to flow water into the repository through the increased permeability pathway associated with the initial fracture whether the pressure is sufficiently high to hold the fracture open or is lower.***

Whether the flow system pulses as postulated by Bredehoeft (1997) is academic. A significant quantity of brine will flow to the repository under this scenario.

If injection continues, WIPP will fill with brine, the pressure will rise to lithostatic, and the fracture will continue to extend outward beyond WIPP. Brine in the repository will lead to gas generation, tending to further increase the pressure.

CHAPTER 5 WIPP at High Pressure

As alluded to above, a different scenario occurs when the pressure in WIPP is at, or near, lithostatic. To those unfamiliar with WIPP, such high pore pressures may seem unusual. However, gas generation within the repository can raise the pressure. Figure 5.1 is a plot of pressure versus time for a set of realizations from PA. It shows a number of realizations in which the pressure was at or near lithostatic.

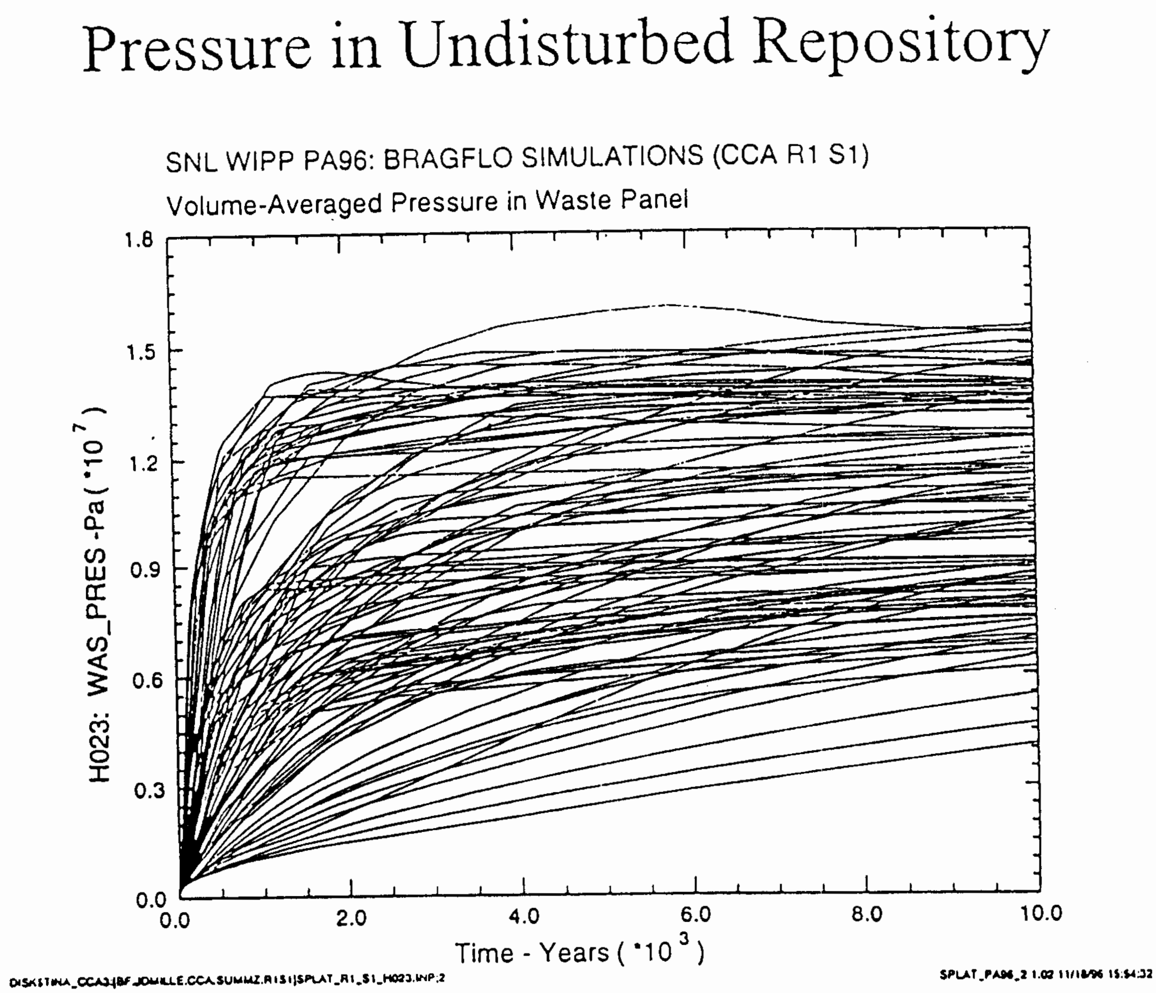

Figure 5.1. Pressure in WIPP (from WIPP PA).

At high pressure, a leaking injection well can create a hydraulic fracture that will extend into the repository and remain open. Such a well can produce flow that will move a substantial amount of brine into WIPP. We model this scenario by 1) creating a hydraulic fracture between the leaking well and WIPP using LEFM, and 2) examining the flow that might occur should this happen using a flow model. We have made a few changes in the model from the Bredehoeft (1997) March Report. These changes are made to address some of the criticisms by Swift et al. (1997). Conceptually the model is similar to that proposed earlier.

The Model

We conceptualize the model in the following manner:

1. We start with the region with virgin anhydrite permeability— $\approx 10^{-19}$ m^2.

2. In creating the hydraulic fracture we use LEFM to define the region fractured. In this instance we will assume that the injection well is off center, nearer one edge of the fracture, and that the fracture has a diameter of 6 km which extends to include WIPP. We give the fracture the permeability observed for the Hartman # 2 Bates well— $\approx 3 \times 10^{-12}$ m^2 (3×10^{-5} m/sec). An alternative procedure would be to use the cubic fracture flow law to calculate an equivalent permeability for the fracture from the aperture predicted by the LEFM model. Use of this alternative procedure indicates an even higher equivalent permeability for the fracture.

3. We hold the pore pressure in WIPP at lithostatic— $\approx$ 14.7 MPa. (We realize that as flow occurs to WIPP the pore pressure within the repository will increase. Our intent is not to predict the pressure in WIPP, but rather to see how much flow might occur through a hydrofrac.)

4. We hold the well head injection pressure at 9.7 MPa (1410 psi); (This translates to a pressure approximately 2 MPa above lithostatic at the depth of WIPP.)

5. For the flow calculations we use a storage coefficient of 10^{-5}. (Swift et al.(1997) criticized Bredehoeft's March Report for using steady flow for the analysis.)

The model assumptions are summarized as:

Table 5.1 Model Assumptions

		Fracture	Pressure	Well @ WIPP depth
Hydraulic Conductivity	K	3×10^{-5} m/sec		
Specific Storage	S_s	10^{-5}		
Well Head			9.7 MPa	16.7 MPa
WIPP Pressure			14.7 MPa (lithostatic)	
Fracture Initiation			14.7 MPa (20 bars above far field)	
Fracture Domain		6 km (diameter)		

With these assumptions we model the system.

Model Results

The model suggests significant flow to WIPP; the results are not significantly changed from Bredehoeft (1997):

Table 5.2. Flow to WIPP—repository at lithostatic pressure.

	Distance from WIPP	Well-head pressure (psi)	Permeability m^2	Flow rate m^3 / yr
Model	3.4 km	1410	3×10^{-12} (3×10^{-5} m/sec)	75,000

Figure 5.2 is a plot of the head distribution associated with this model after one year of injection. Within the domain of the fracture the flow has reached steady-state; outside the fracture the flow continues to equilibrate to the far field pressure boundary. However, the flow outside the domain of the fracture is insignificant.

Figure 5.3 is a plot of the flow to WIPP versus time. Starting with a flow field with no gradient at time zero the flow reaches a steady state in approximately 150 days. The rate is large, approximately 75,000 m^3/yr. Since WIPP, once consolidation takes place, has a pore space of approximately 50,000 m^3, this is a significant quantity of flow.

Once WIPP fills, the hydrofrac will continue to extend outward from the repository. This leads to the scenario described in Chapter 6.

Concluding Remarks

This analysis indicates that 1) if the repository were near lithostatic pressure, and 2) at the same time an injection well some miles away leaked in such a way that pressure above lithostatic were imposed on Marker Bed 139, a high permeability hydraulic fracture could connect between the well and WIPP. The pressure everywhere would be at lithostatic, or above, and the fracture would remain open. In this instance a steady flow field is created in approximately ½ year, and it is maintained as long as the well continues leaking, or until the pressure in WIPP builds up to approximately that at the injection well. In the process WIPP will receive a large inflow of brine. If the injection continues the frac will continue to extend beyond the repository.

This is one of the Hartman type scenarios that poses a significant problem. This scenario is much like drilling into a Castile brine reservoir in terms of its impact on WIPP. Of course, this scenario does not occur until the pressure within the repository builds up to near lithostatic, which in the undisturbed state may not occur until 1000 years after closure, or longer.

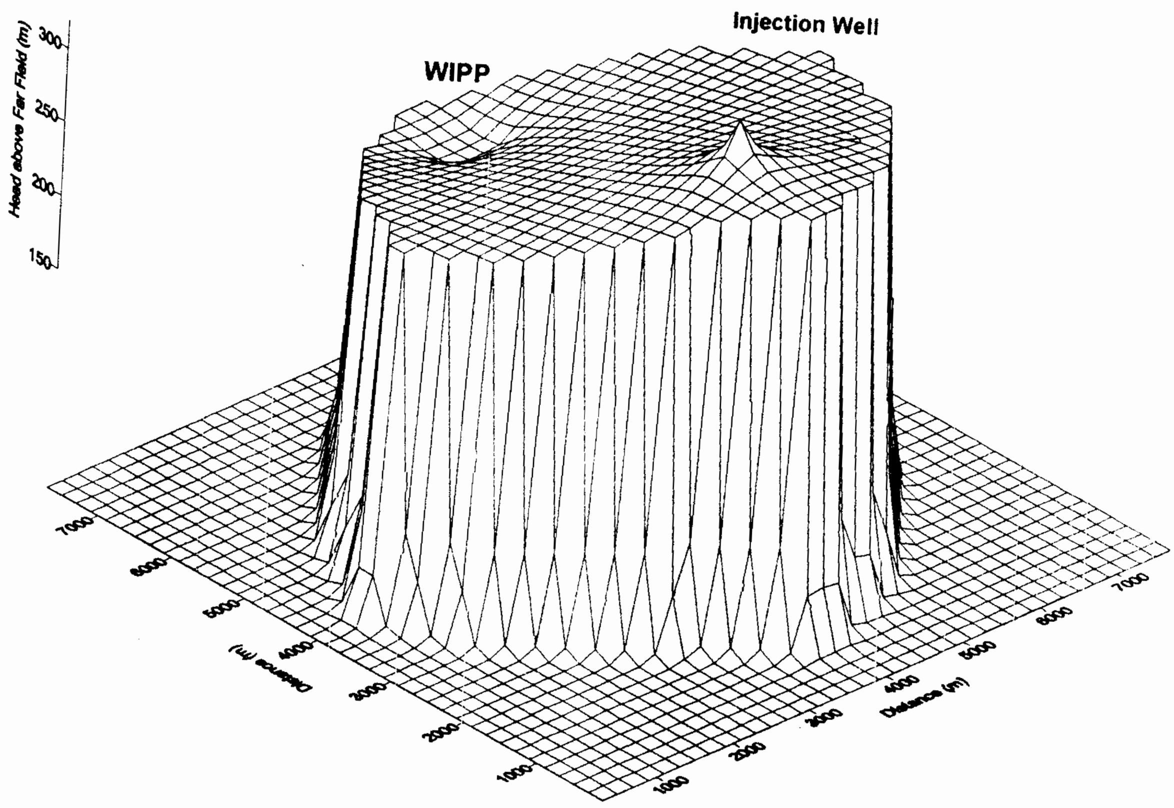

Figure 5.2. Head distribution after one year of injection. On this plot the area that is hydraulic fracture is clearly shown.

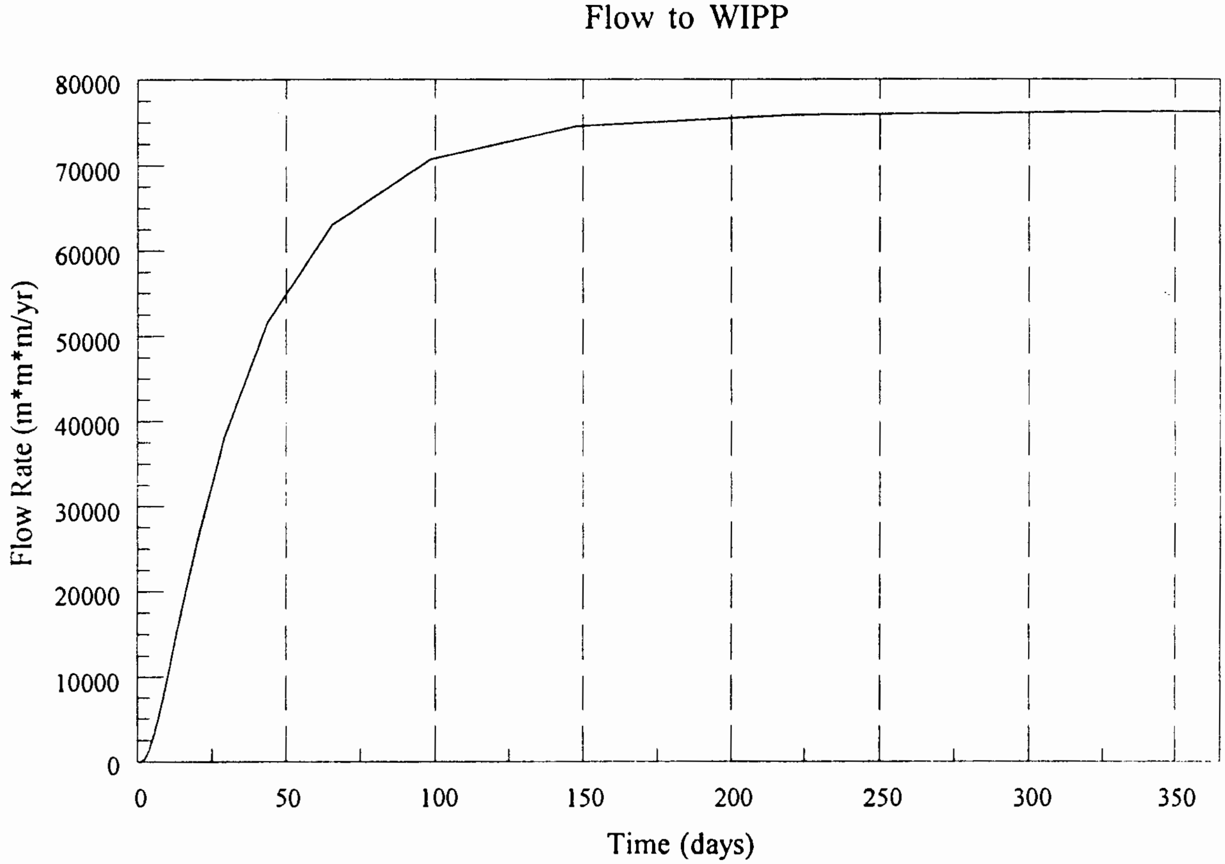

Figure 5.3 Flow to WIPP as a function of time. The flow becomes essentially steady-state in approximately 150 days.

Chapter 6 The Two-Well Scenario

Introduction

Bredehoeft (1997) identified a two-well scenario that has the potential to move a plume of contamination outward from WIPP across the regulatory boundary. In this scenario a well is injecting at pressures above lithostatic on one side of WIPP. On the other side of the repository is a poorly plugged well open to marker beds associated with the repository. The scenario is: 1) the injection well leaks and causes hydraulic fracturing of a marker bed associated with WIPP, 2) the repository fills with brine and comes to an ambient pressure approaching that of the injection well, 3) the hydraulic fracture continues to grow outward and reaches an unplugged well on the opposite side of WIPP, and 4) a coupled two-well, in-out, flow field is established.

This flow field, with injection on one side of WIPP and flow out on the other side, creates flow through the repository. This flow through the repository moves wastes to the regulatory boundary. Transport occurs quickly.

In this analysis, similar to Bredehoeft (1997), we assume that WIPP is passive. It fills with brine and reaches a pressure dictated by the two wells. Flow occurs through the marker bed, is diverted through the repository, and back into the marker bed. This occurs because the repository and the disturbed rock zone (DRZ) provide a high permeability pathway for fluids where it exists. Contaminants in solution in the repository are moved out and transported downstream in the marker bed.

This scenario will quickly move contaminants to the land withdrawal boundary with approximately the same concentration as the brine within WIPP. The concentration at the boundary is entirely dependent upon the solubility of the waste in the repository brine. Sorption in the marker bed can only slow the transport to the boundary. Since we are assuming flow in Marker Bed 139 which is approximately 1 m thick, it seems conservative to assume no dispersion and retardation. With a 10,000 year time frame the retardation associated with sorption, unless it is very large, does not matter so long as the injection continues for some period. The ultimate volume of contaminant reaching the boundary depends upon how long the injection persists.

Two-Well Model

We modeled this scenario, including the contaminant transport. We make a number of assumptions; these are summarized in Table 6.1:

Table 6.1 Model Assumptions

		Fracture	Far Field	WIPP	Well
Hydraulic Conductivity (equivalent permeability of crack)	K	3×10^{-5} m/sec	0	same as fracture	
Specific Storage	S_s	0 (steady flow)	0		
Porosity		0.04 (this value indicated in the CCA for hydrofraced anhydrite)			
Pressure		14.7 MPa (lithostatic)		ambient	**Injection Well** 9.7 MPa surface 16.7 Mpa @ MB **Outflow Well** 0 MPa surface 14.7 MPa @ MB
Well Flow Rates		model result (2.3×10^{-3} m^3/sec: in = out, steady flow)			
Fracture Domain		8 km diameter			
Dispersion Coefficient		0			
Sorption`		0 (no retardation)			

With pressures at both wells specified (inflow & outflow wells) we adjusted the flow rate of the outflow well until the head remains above lithostatic throughout the flow domain. The resulting flow rate is approximately that determined for the scenario in Chapter 5.

Swift et al. (1997) commented that one could not maintain a lithostatic pressure in the Marker Bed at the outflow well. This is not true; one simply has to have a head loss in the well equal to the difference between 1) hydrostatic head at the depth of the marker bed, and 2) lithostatic head at this point. A well with an equivalent open diameter between 1 and 2 inches provides the necessary head loss to maintain the bottom of the well at lithostatic pressure.

WIPP Contaminant Concentration

The WIPP Sensitivity Analysis (CCA Appendix SA) contains plots of contaminant concentration, for a full set of PA realizations, in both Salado and Castile brine with magnesium oxide backfill. In the first 2000 years, typical concentrations for the set of PA realizations ranged from 10^{-2} to 10^{-3} EPA Units/m^3. Figure 10.1 is the plot of contaminant concentration in WIPP in EPA Units versus time. For the purposes of this analyses we use a concentration of 10^{-3} EPA Units/m^3—at the low end of the typical PA calculations.

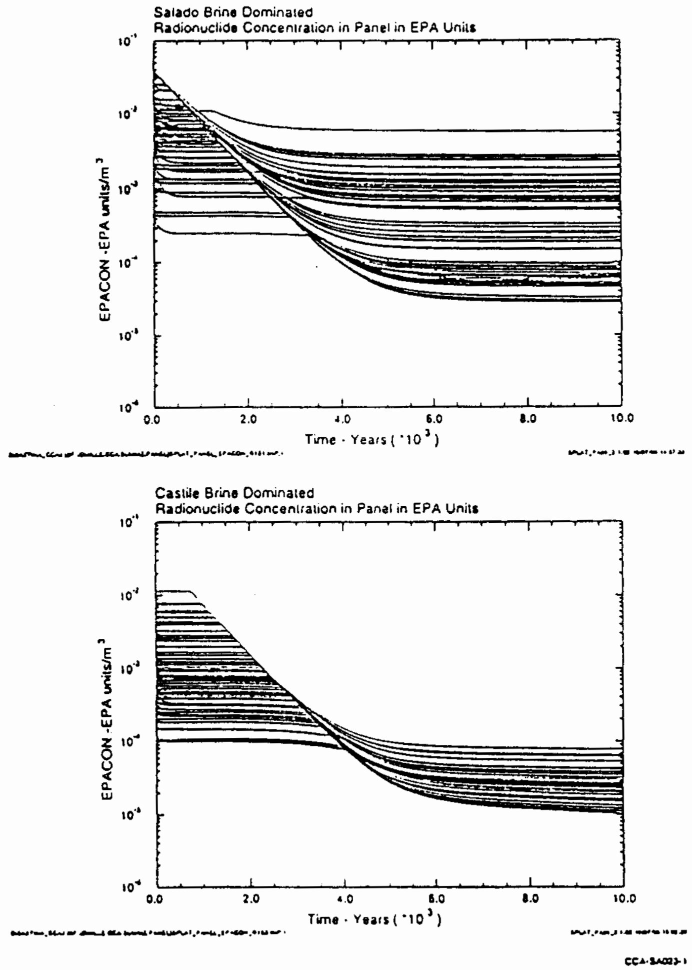

Figure 6.1 Radionuclide concentration in EPA Units/m^3 in WIPP with MgO backfill (from WIPP Appendix SA).

Model Results

For the transport calculations we use the code, JDB-MOC, a method of characteristics code developed for PCs (Bredehoeft, 1994). This code is based upon an earlier code MOC (Konikow and Bredehoeft, 1978).

Figure 6.2 is a plot of the hydraulic head showing the two wells. Flow is 1) in at the injection well, 2) through the fractured marker bed, 3) through WIPP, 4) back into the marker bed, and 5) to the outflow well. WIPP is positioned between the two wells. The repository is passive; its pressure is dictated by the flow field between the two wells. As flow moves through WIPP, contaminants are moved by the flow field.

Figure 6.3 is a plot of contaminant concentration near the outflow well; concentration is expressed as a percent of the concentration in WIPP. One sees the first arrival of the contaminants in approximately 7.5 years, that is followed by a build-up in concentrations. Concentrations at the outflow well are reduced by the radial flow mixing of uncontaminated with contaminated brine at the well.

The system is modeled without either dispersion or sorption in the marker bed. The marker bed is only one meter thick; both effects may be limited in such a thin bed, especially since it is hydraulically fractured. Dispersion will spread the plume reducing the maximum concentrations; the total mass transported is the same; it is simply spread out by dispersion. Sorption creates retardation, the plume moves slower than the fluid velocity predicts. With sorption, the plume still gets there; it moves more slowly.

Figure 6.4 is an isometric projection of the plume. Again, the concentration is plotted as a percentage of the concentration in WIPP. The plume is as wide as the repository, approximately 750 m. One can see that a substantial volume of contaminated brine crosses the regulatory boundary.

Figure 6.5 is a plot of the integrated releases from WIPP, in EPA units, at differing distances. One must integrate the mass of contaminate to produce Figure 6.5. This plot indicates when the transport of contaminants would violate the EPA standard. The modeling suggests that 50 EPA Units cross the regulatory boundary in approximately 13 years.

Concluding Remarks—Back of the Envelope Check

The transport associated with this scenario is so large that we wish to check the model with a simple calculation. The velocity of flow is given by Darcy's Law:

$$v = (K/n)\, \partial h/\partial l$$

where v is the velocity of flow;
K is the hydraulic conductivity;
n is the porosity;
$\partial h/\partial l$ is the hydraulic gradient.

The flux of fluid is given as:

$$Q = v\, n$$

To obtain the flow into or out of the WIPP, we integrate the flux in the marker bed either upstream or downstream from the repository. Since the flow field is simple and one dimensional in the vicinity of the repository, the flux through WIPP is easily derived:

$$Q_{\text{total thru WIPP}} = Q * W_{\text{normal to flow}} * H_{\text{marker bed}}$$

where W is the width of WIPP normal to the flow field; and

H is the height of the maker bed.

We can substitute numbers in this equation:

$v = 0.8 \times 10^{-5}$ m/sec;
$n = 0.04$
$W = 750$ m
$H = 1$ m

therefore: $Q = 2.4 \times 10^{-4}\ m^3/sec$; or $21\ m^3/day$; $7600\ m^3/year$.

The flow through the repository is approximately 10 % of the well flow. At this rate one repository pore volume flows through WIPP in 6.6 years; this flow has the potential to totally replace the fluid in the repository (the repository after consolidation has a pore volume of approximately 50,000 m^3). One pore volume of repository brine with a concentration of contaminants of 10^{-3} EPA Units/m^3 contains 50 EPA units; in this scenario this dissolved waste is transported to the land withdrawal boundary. (One EPA Unit of contaminant, with a probability of 10 %, violates the EPA licensing criteria.) ***It is easy to see that this scenario poses problems for WIPP.***

It is hard to predict the concentration of contaminants in the repository in a scenario in which it is rapidly flushed. With rapid flushing the contaminant concentrations will be limited by the solution reaction kinetics. We have not extended the release plots beyond the initial 50 EPA Units in solution for this reason.

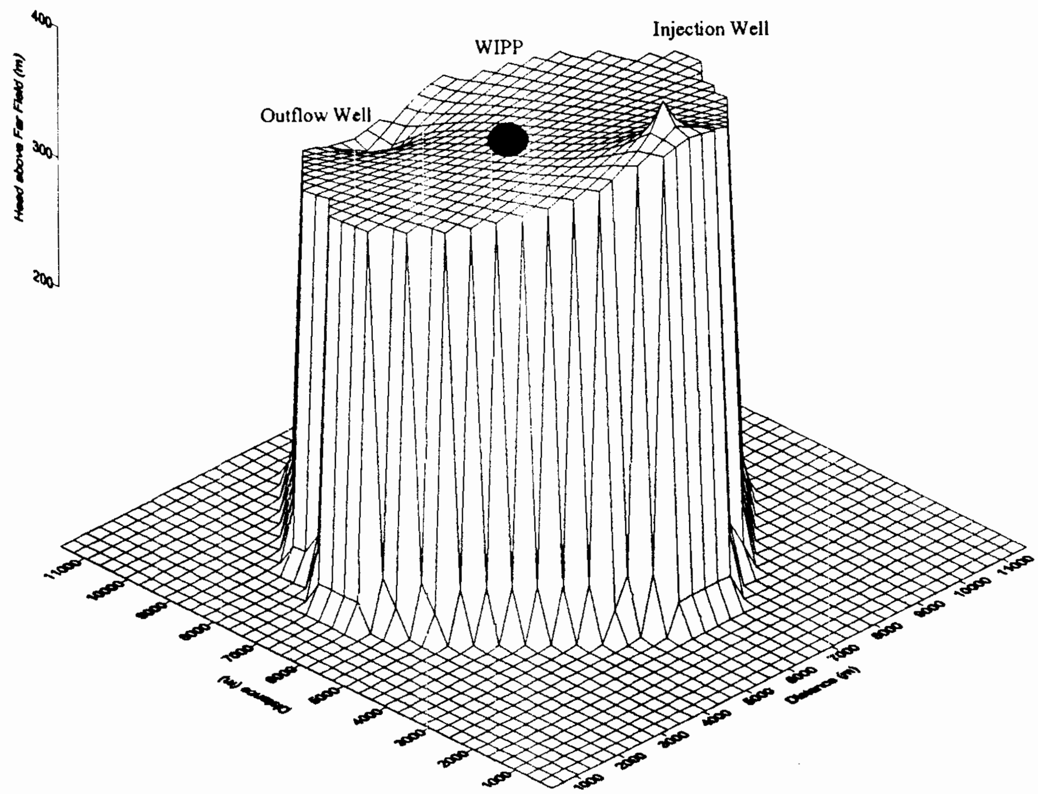

Figure 6.2 Head distribution for the two-well scenario. The area hydrofraced area is apparent on this figure.

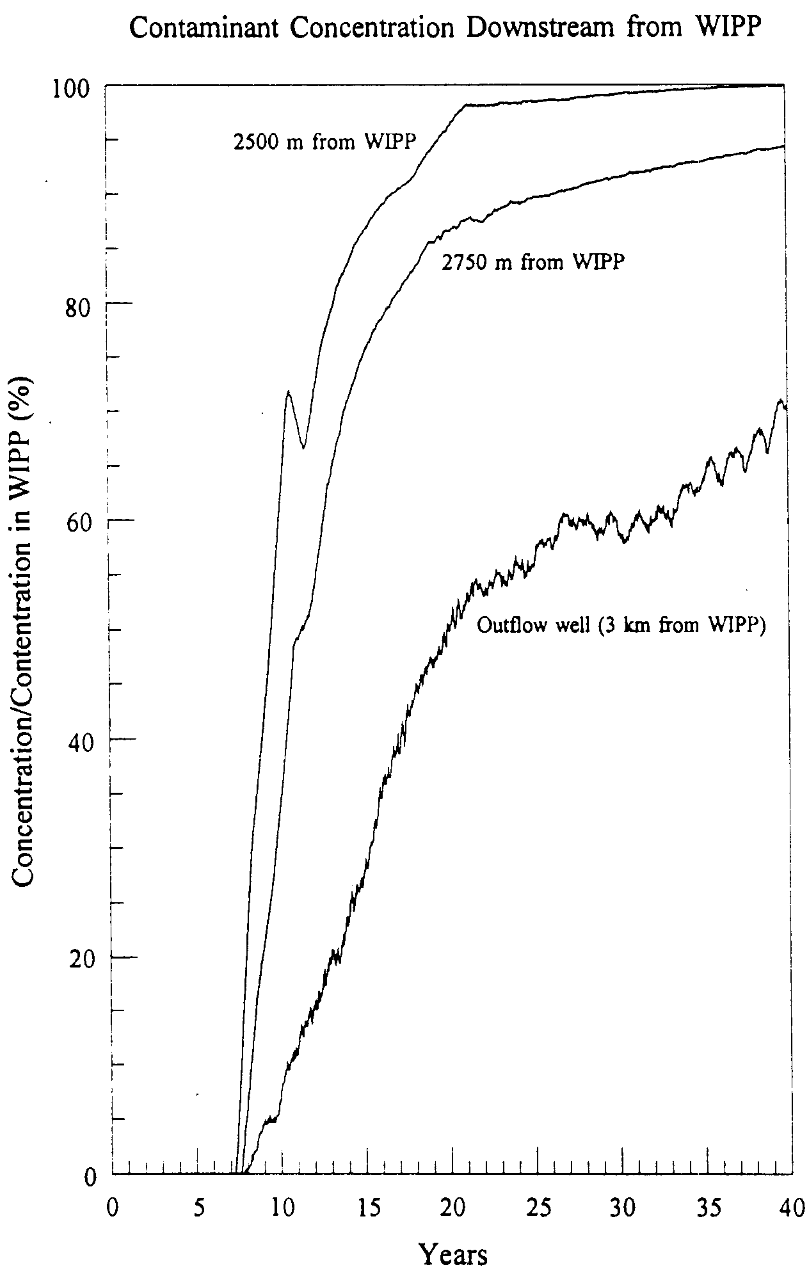

Figure 6.3 Plot of contaminant concentration at differing distances from WIPP. Concentrations are plotted as a percent of the concentration in WIPP.

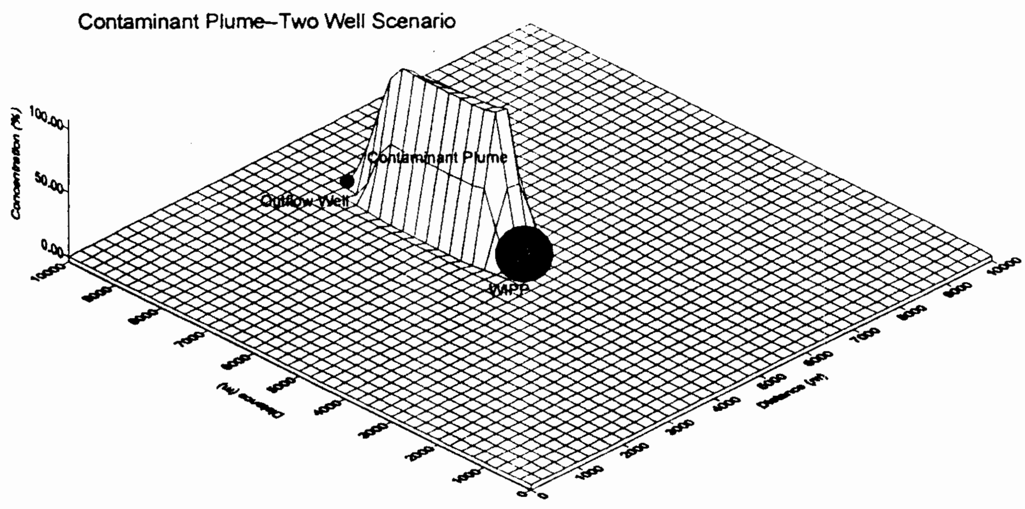

Figure 6.4 Isometric projection of the contaminant plume in the two-well scenario.

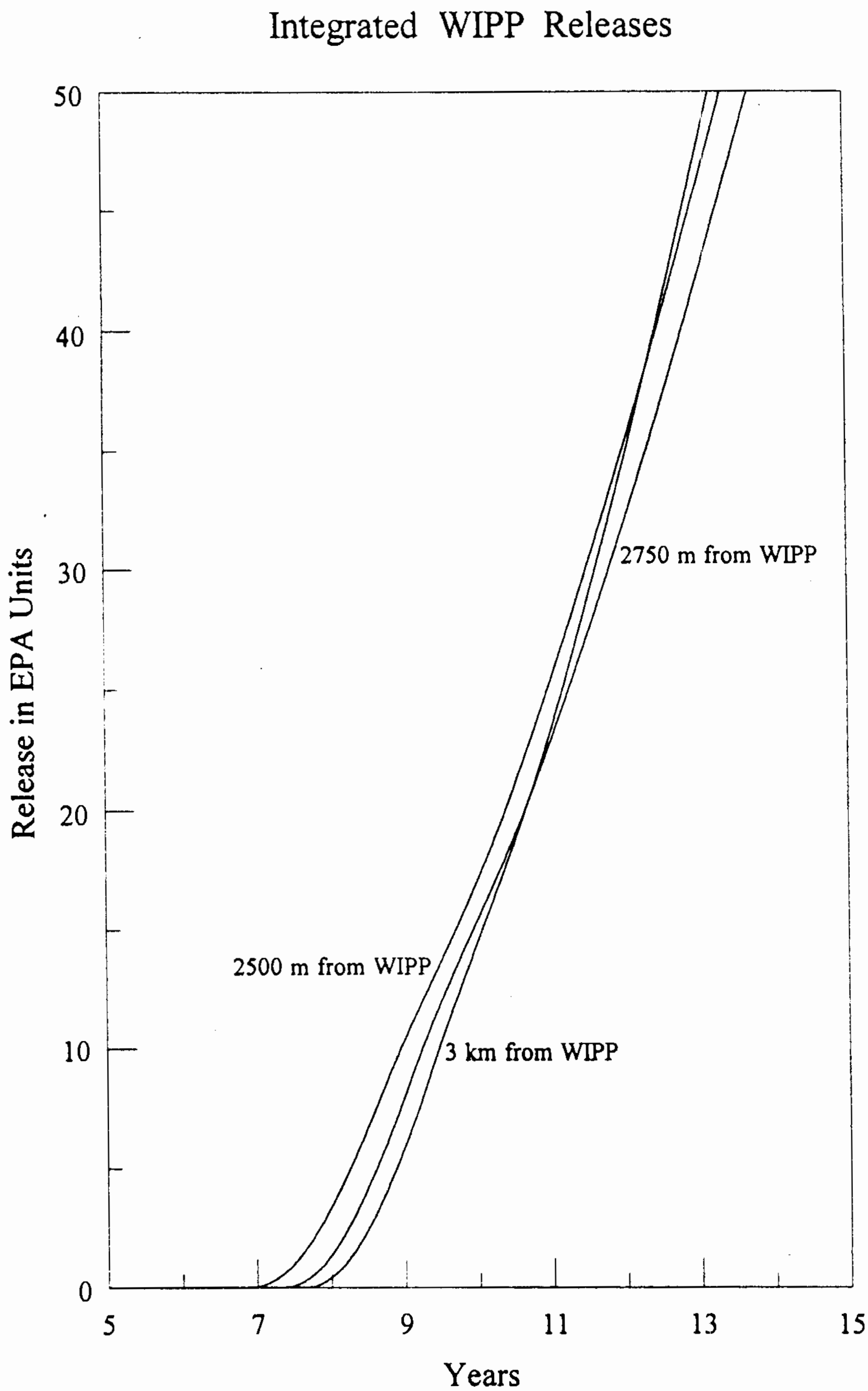

Figure 6.5 Plot of the contaminant mass released from WIPP. The contaminant concentration in WIPP is 10^{-3} EPA Units/m^3 for this result. The three curves should converge with time; the spread in the curves at later times is some measure of the model error.

Chapter 7 Conclusions

The Hartman # 2 Bates well Blowout

Our review of the data continues to indicate that the blowout of the Hartman # 2 Bates well is best explained as a hydrofrac in the lower Salado Formation that extends from the Texaco Rhodes-Yates Waterflow to the well. This is the consensus of most investigators that examined the empirical data, including us.

DOE and Sandia dismiss the interpretation that a hydrofrac happened at the # 2 Bates well.

LEFM versus BRAGFLO

Linear Elastic Fracture Mechanics (LEFM) is a widely used and accepted model for fractures including hydrofracs. BRAGFLO when compared to LEFM underestimates fracture radius by a factor of 5 times. Our review of the Sandia data does not present sufficient information to select the "porosity model" used in BRAGFLO over the "aperture model". Numerous internal documents indicates Sandia's concern about this problem. ***BRAGFLO in its current implementation is an inadequate model to predict the extent of hydraulic fractures.***

Stoelzel and Swift (1997) use BRAGFLO to compute hydrofrac radius. Their analysis is non-conservative in that they:

1. assume uniform permeability in the entire annular space between the borehole rock wall and the casing; and
2. allow fluids to hydrofrac all the marker beds simulataneously.

These assumptions minimize the hydrofrac radius; they do not represent what happened at the Hartman # 2 Bates well.

Scenarios

We conclude that three well injection scenarios described in Bredehoeft (1997) still pose problems; these are:

1. ***hydrofrac extends from a leaking injection well into WIPP at low pressure;***
2. ***hydrofrac extends from a leaking injection well into WIPP when it is at lithostatic pressure;***
3. ***hydrofrac extends through WIPP and encounters a poorly plugged well that leaks upward.***

Scenario number 3 has the highest negative consequences. It shows that the containment criteria are significantly violated in a few years.

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